Spatial Extent of Contamination, Toxicity and Associated Biological Effects in Puget Sound Sediments

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Abstract

Analyses were performed to quantify chemical concentrations, acute toxicity in laboratory tests, and the structure of benthic infauna communities in sediments from 300 randomly chosen locations in Puget Sound during 1997 to 1999. Samples of surficial sediments were collected from the vicinity of the U.S./Canada border to the inlets of southern Puget Sound and Hood Canal as part of a joint research program of the National Oceanic and Atmospheric Administration and Washington State Department of Ecology. The study was designed to provide information on the severity, spatial patterns, and spatial extent of contamination, toxicity, and degraded benthos and the relationships among these measures of sediment quality. The weight-of-evidence from the three complimentary analyses suggests that degraded conditions (high chemical concentrations, significant toxicity, and adversely altered benthos) occurred in samples that represented about 1% of the total area. These conditions invariably occurred in samples collected within urbanized bays and industrial waterways in which degraded conditions had been reported in previous studies. Sediments with good quality (as indicated by no toxicity, no contamination, and abundant and diverse infauna) occurred in 42% of the total study area. Sediments in which moderate or intermediate degrees of degradation occurred represented 57% of the study area (9% with significant toxicity and high chemical contamination, but abundant infauna; 48% with significant toxicity or high chemical contamination (i.e., not both), but abundant infauna). This large area with intermediate levels of sediment degradation underscores the need for continued surveillance to assess changes in sediment condition over time.

Introduction

Toxic substances introduced into estuarine ecosystems, such as Puget Sound, can bind to suspended particles, settle to the bottom, and become incorporated into deposited sediments. Toxicants associated with sediments can represent a potential toxicological threat to the resident biota if concentrations become sufficiently elevated. Toxic chemicals are known to occur in a wide range of concentrations in surficial (recently deposited) sediments of Puget Sound. Although contaminant levels in some areas have been well characterized with data from many previous studies, other regions were poorly known. Also, despite source controls initiated in recent decades, some areas remain highly contaminated and thus pose a serious threat to the estuarine ecosystems of the Sound.

Despite the availability of historical data on sediment quality from many studies in regions of Puget Sound, none of these historical data were collected with methods that allowed estimates to be made of the surficial or spatial extent of degradation. Often, studies were performed in the vicinity of specific point sources or other focused areas; thus, precluding analyses of the data to determine the actual size and spatial dimensions of the degraded areas on a Sound-wide basis.

The Washington State Department of Ecology (Ecology) Marine Sediment Monitoring Team has conducted the Sediment Monitoring Component of the Puget Sound Ambient Monitoring Program (PSAMP) since 1989. This program used the "Sediment Quality Triad" approach of Long and Chapman (1985) to determine relative sediment quality in Puget Sound. Ecology established baseline data for toxicity and chemical contamination of Puget Sound sediments (Llansó and others 1998a) and characterized infaunal invertebrate assemblages (Llansó and others 1998b) at 76 selected monitoring stations throughout Puget Sound. A portion of this baseline work is continuing at a subset of ten stations at the present time.

The National Status and Trends (NS&T) Program of NOAA has conducted bioeffects assessment studies in more than 30 embayments and estuaries nationwide since 1990 (Long and others 1996; Long, 2000). All of these studies followed a random-stratified sampling design. Most involved use of the triad approach to estimate the spatial extent, magnitude, and spatial patterns in relative sediment quality and to determine the relationships among measures of toxicity, chemical contamination, and benthic infaunal structure within the study areas. In 1996, Ecology and NOAA entered into a three-year cooperative agreement, combining the sediment monitoring and assessment programs of the two agencies into one large survey to quantify the magnitude and extent of toxicity and chemical contamination of sediments throughout Puget Sound utilizing NOAA's random-stratified sampling design and the "Sediment Quality Triad" approach.

The shared goal of this study for both the PSAMP Sediment Monitoring Component and NOAA's nationwide bioeffects assessment program was to characterize the ecotoxicological condition of sediments, as well as benthic infaunal assemblage structure, as a measure of adverse biological effects of toxic chemicals in Puget Sound.

Specific objectives of the program in Puget Sound were:
1. Determine the incidence and severity of sediment toxicity.
2. Identify spatial patterns and gradients in sediment toxicity and chemical concentrations.
3. Estimate the spatial extent of toxicity and chemical contamination in surficial sediments as percentages of the total survey area.
4. Describe the composition, abundance and diversity of benthic infaunal assemblages at each sampling location.
5. Estimate the apparent relationships between measures of sediment toxicity, toxicant concentrations, and benthic infaunal assemblage indices.
6. Compare the quality of sediment from northern, central, and southern Puget Sound measured in the three phases of this study.

In this presentation, estimates of the spatial extent of toxicity and chemical contamination of Puget Sound sediments are displayed separately, and compared with sediment data collected nationally. These data are then combined with benthic infaunal results to display a spatial characterization of the 2363 km^2 Puget Sound study area based on a "weight-of-evidence" characterization of the "Sediment Quality Triad" parameters.

Methods

All details of the methods used in the program are described in technical reports (Long and others 1999, 2000, in prep.) and summarized in the 1998 Puget Sound Research Conference Proceedings (Long and Dzinbal, 1999). Therefore, only a brief summary is provided in this report. During a three-year period, samples were collected for analyses throughout most of the Puget Sound region (Figure 1). Briefly, the area sampled during 1997 extended from the U.S./Canada border south to Port Gardner Bay. In 1998, samples were collected within a region extending from the Port Gardner area to Des Moines, including the central basin and the inlets west of Bainbridge Island. In 1999, the area sampled extended from the Des Moines area to the southern limits of the Sound and included Hood Canal.

Sediments were collected with a double 0.1m^2 van-Veen grab. Sufficient amounts of surficial material (upper 2-3 cm) were removed from multiple deployments of the grab at each station to form a composite sample for chemical analyses and four toxicity tests. Benthic infauna were collected with a single deployment of the 0.1 m^2 sampler at each station. Sorting of taxonomic groups retained on 1.0 mm sieves, identification to species level (when possible), and enumeration of organisms were done with standard protocols developed for Puget Sound (PSEP, 1987). Indices of the diversity and abundance of the macrobenthic infauna were calculated.

Chemical analyses were performed for many trace elements (including potentially toxic metals), polynuclear aromatic hydrocarbons (PAHs), pesticides, phenols, phthalate esters, polychlorinated biphenyls (PCBs), other organic toxicants, total organic carbon, and grain size. Protocols were used that satisfied

requirements of both NOAA (Lauenstein and Cantillo, 1993) and Ecology (PSEP, 1986, 1987, 1995, 1996a,b,c,d). Chemical concentrations were compared against Washington State Sediment Management Standards (Chapter 173-204 WAC) and effects-based, informal guidelines developed by NOAA (Long and others 1995).

Toxicity tests were performed with widely accepted protocols. Amphipod survival tests followed protocols of the ASTM (1993), using the species *Ampelisca abdita*. Sea urchin fertilization tests of pore waters followed protocols of the U. S. Geological Survey (Carr and Chapman, 1992), using gametes of the purple urchin *Strongylocentrotus purpuratus*. Cytochrome P-450 assays of the light produced by luciferase in a reporter gene system (RGS) of cultured human liver cells was conducted on organic solvent extracts, following standard protocols (Anderson and others 1995, 1996; APHA, 1996; ASTM, 1997). Microbial bioluminescence (Microtox^{tm}) tests were performed with protocols initially developed for Puget Sound (PSEP, 1995; Schiewe and others 1985) to determine inhibition of light production. These tests were run on a portion of the extracts prepared for the cytochrome P-450 assays. Results of the toxicity tests were compared to those from negative (non-toxic) controls to assign statistical significance (Long and others 1996).

Results

Chemical Contamination

The spatial extent of chemical contamination was estimated by comparing the chemical concentrations in the samples to Washington State Sediment Management Standards and to guidelines developed for NOAA. The sizes of strata in which the guidelines were exceeded were summed (Table 1). Fourteen percent of the 300 samples had one or more chemical concentrations that exceeded an Effects Range-Median (ERM; Long and others 1995) value. These samples represented an area of 41 km^2, or about 1.3% of the total area (2363 km^2) that was sampled during the three-year program. In contrast, 26% of samples nationwide from rivers, lakes, estuaries, and coastal areas compiled by the U.S. Environmental Protection Agency (EPA) had similar chemical concentrations (U.S. EPA, 1997).

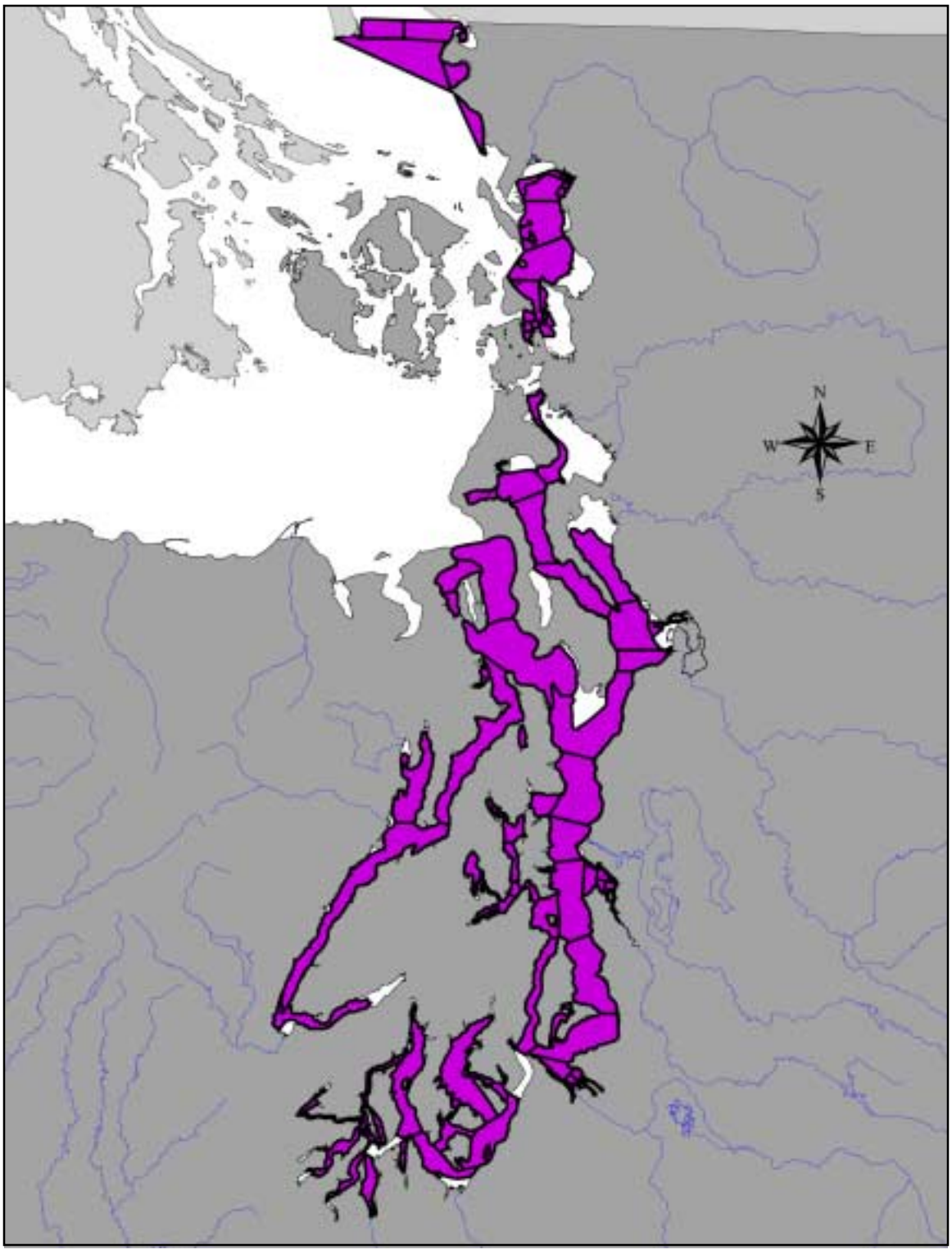

Figure 1 Map of Puget Sound study area for the NOAA/PSAMP Cooperative Agreement. The strata sampled during 1997-1999 are outlined.

Mean ERM quotients take into account the concentrations of 25 individual chemicals normalized to (i.e., divided by) the respective ERM values (Long and others 1998). Values greater than 1.0 were detected in 2% of the Puget Sound samples, representing about 0.2% of the total survey area. Based upon data compiled from estuarine studies conducted elsewhere in the nation by NOAA and U.S. EPA, about 5% of samples had equivalent levels of contamination (Long and others 1998).

Relative to the Washington State Sediment Management Standards (SQS and CSL values; Chapter 173-204 WAC), the samples with chemical concentrations greater than these values represented about 34% and 28.6% of the total survey area, respectively. No equivalent data are available on a national scale using these two sets of values.

Table 1. Spatial extent of chemical contamination of Puget Sound sediments and comparisons with national data bases.

Chemical Index	Puget Sound	National Database
One or more chemicals > ERM values	14% of 300 41/2363 km^2 (1.3% of area)	26% of 21,000[a]
Mean ERM quotients > 1.0	2% of 300 6/2363 km^2 (0.2% of area)	5% of 1068[b]
One or more chemicals > SQS values	45% of 300 134/2363 km^2 (34% of area)	nd
One or more chemicals > CSL values	35% of 300 106/2363 km^2 (28.6% of area)	nd

[a] U.S. EPA, 1997
[b] Long and others 1998
nd = no data

Toxicity

Estimates of the spatial extent of toxicity of Puget Sound sediments and comparison with national databases are displayed in Table 2. In Puget Sound, one sample out of the 300, representing less than 0.1% of the total survey area tested, indicated a highly toxic response in the amphipod survival tests. In contrast, two estimates of the spatial extent of toxicity in amphipod tests on a national scale ranged from 5.9% to 7.3% of the respective study areas (Long 2000). Samples in which results of the urchin fertilization tests of 100% pore waters were highly significant represented about 4% of the area in Puget Sound whereas they represented about 25% of the areas tested nationally (Long 2000). Similarly, the spatial extent of highly significant results in the Microtox^{tm} (microbial bioluminescence) tests was much smaller in Puget Sound (<1% of the area) than elsewhere in the nation (39%; Long 2000). Using two numerical criteria to aid in interpretation of the cytochrome P-450 induction assays (Long and others 1999), results with sediments from Puget Sound and elsewhere in the nation were relatively similar. However, samples that indicated the highest responses represented about 3% of the Puget Sound survey area, whereas they represented about 9% of the area in surveys conducted elsewhere.

Table 2. Spatial extent of toxicity of Puget Sound sediments and comparisons with national data bases (percent of area (km^2) with high toxicity).

Toxicity test	Puget Sound	National database[a]
• amphipod survival	<0.1% of 2363 km^2	5.9% of 7379 km^2 7.3% of 64,677 km^2
• urchin fertilization	4.0% of 2363 km^2	25.3% of 6838 km^2
• microbial bioluminescence	0.4% of 2363 km^2	39% of 7160 km^2
• cytochrome P-450 > 11.1 µg/g	24.8% of 2363 km^2	20% of 8024 km^2
• cytochrome P-450 > 37.1 µg/g	2.8% of 2363 km^2	9% of 8024 km^2

[a]Long 2000

Benthic Infauna

Indices of total abundance, major taxa abundance, taxa richness, Pielou's evenness (J'), and Swartz's Dominance Index (SDI) were generated for each sample, along with a list of dominant taxa found in each sample. In the absence of accepted critical values for benthic indices in Puget Sound, best professional judgement was used to identify stations that appeared to have infaunal populations impacted by either anthropogenic or natural stressors. That is, the samples from these stations had relatively low index values and were populated with species suspected of being pollution/stressor tolerant).

Triad Synthesis—"Weight-of-Evidence" Approach

Results of the "Sediment Quality Triad" of analyses (i.e., chemical, toxicity, and benthic infaunal data) were combined to form a "weight-of-evidence" for assessing the relative quality of the 300 Puget Sound sediment samples. Summary data are presented for each of the three years of the study and for 300 stations combined (Table 3). There were 39 samples in which highly significant results in one or more toxicity tests were recorded and one or more chemical concentrations exceeded a state standard or NOAA guideline, and in which there was a relatively depauperate benthic infaunal assemblage. These samples are considered the most degraded among the 300 samples tested. Most of these samples were collected in the 1998 survey of central Puget Sound, which included Elliott Bay, Sinclair Inlet, and the urbanized inlets and basins west of Bainbridge Island. However, because these 39 samples were collected within relatively small strata, they represented only about 1% of the total survey area.

There were another 39 samples in which highly significant toxicity was observed in one ore more tests and one or more chemical concentrations exceeded the applicable standards or guidelines, but the benthos was apparently unaffected, i.e., appeared to be diverse and abundant. Thus, these samples suggested that although the sediments had elevated chemical concentrations and were toxic in the laboratory tests, verification of degraded conditions was not apparent among the resident benthos. Therefore, the quality of these sediments was somewhat better than in those in the first category. Most of these samples were collected in 1997 and 1998 in northern and central regions of the Sound, respectively, and represented about 9% of the total survey area.

The greatest proportion of the 300 samples (141) were either toxic or contaminated, but not both, and supported a diverse and abundant benthos. Some of these samples may have had elevated toxicant levels that were not bioavailable and, therefore, did not indicate toxicity. Other samples may have been toxic because of the presence of substances for which chemical analyses were not performed. Finally, the remaining samples (81) were non-toxic, not contaminated, and supported a rich benthos; thus representing the least degraded conditions. Together, the 222 samples in these latter two categories represented a large majority (about 90%) of the total survey area.

Table 3. Spatial extent of "degradation" of Puget Sound study areas based upon the "Sediment Quality Triad" of chemistry, toxicity, and benthic infaunal data.

Indices of sediment quality	1997 Northern Puget Sound (773.9 km^2)	1998 Central Puget Sound (731.7 km^2)	1999 Southern Puget Sound (857.7 km^2)	Total Puget Sound Study Area (2363 km^2)
Highly significant toxicity, high chemical contamination, altered benthos				
number of samples	10	18	11	39
area (km^2)	10.3	8.1	4.4	22.8
% of area	1.3	1.1	0.5	1.0
Highly significant toxicity, high chemical contamination, abundant/diverse benthos				
number of samples	16	18	5	39
area (km^2)	81.7	91.6	39.0	212.3
% of area	10.6	12.5	4.5	9.0
Toxic or contaminated (not both), abundant/diverse benthos				
number of samples	53	39	49	141
area (km^2)	530.2	272.6	332.8	1135.6
% of area	68.5	37.3	38.8	48.1
Non-toxic, non-contaminated, abundant/diverse benthos				
number of samples	21	25	35	81
area (km^2)	151.7	359.3	481.4	992.4
% of area	19.6	49.1	56.1	42.0

Conclusions

Data from this survey provided an objective basis for estimating the relative quality of sediments from throughout Puget Sound. Analyses were conducted to estimate independently the degree and spatial extent of chemical contamination, acute toxicity, and adverse benthic impacts throughout all major basins and reaches of Puget Sound. Data were reported as percentages of the survey area in which degraded or un-degraded conditions were recorded, using applicable sets of critical values. Data from the triad of analyses also were combined to assess the relative quality of the sediments, using a weight-of-evidence approach.

Elevated concentrations of potentially toxic substances in the sediments were observed in 1.3 to 34% of the total Puget Sound survey area, depending upon the set of numerical standards that were used. Acute toxicity in the least sensitive test was observed in only one of the 300 samples, representing less than 0.1% of the total study area. Highly significant results in the other toxicity tests also were recorded in a small percentage of the area sampled (1 to 4%). The spatial extent of toxicity in Puget Sound, expressed as percentage of survey area, was typically lower than observed elsewhere in estuarine studies in the USA.

Based upon the weight-of-evidence from the triad of analyses, 39 samples, or about 1% of the Puget Sound survey area, displayed significant toxicity, chemical contamination above state standards, and degraded benthic infaunal communities. Samples in this category were collected in Everett Harbor, the lower Duwamish River, Sinclair Inlet, the Commencement Bay waterways, Olympia Harbor, and along the

Seattle waterfront. In contrast, 81 samples, or about 42% of the survey area, typically those of the deep basins and shallow bays near undeveloped lands, had sediments that were non-toxic, not contaminated, and supported an abundant and diverse benthos. The observation, however, that 180 samples, or about 57% of the survey area had mixed or intermediate results (i.e., one and/or two of the three triad parameters impacted) suggests that there are large areas in need of continued surveillance to assess changes in sediment condition over time.

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